TWO-DIMENSIONAL FINITE-DIFFERENCE MODELING OF BROADBAND REGIONAL WAVE PROPAGATION PHENOMENA: VALIDATION OF REGIONAL THREE-DIMENSIONAL EARTH MODELS AND PREDICTION OF ANOMALOUS REGIONAL PHASES

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ABSTRACT

An important challenge for seismic monitoring of nuclear explosions at low magnitude to verify a nuclear-test-ban treaty is the development of techniques that use regional phases for detection, location, and identification. In order to use such phases, region-specific earth models and tools are needed that accurately predict features such as travel times, amplitudes, and spectral characteristics. In this paper, we present our efforts to use two-dimensional finite-difference modeling to help develop and validate regional earth models for the Middle East and North Africa and to develop predictive algorithms for identifying anomalous regional phases.

To help develop and validate a model for the Middle East and North Africa, we compare data and finite-difference simulations for selected regions. We show that the proposed three-dimensional regional model is a significant improvement over standard one-dimensional models by comparing features of broadband data and simulations and differences between observed and predicted features such as narrow-band group velocities.

We show how a potential trade-off between source and structure can be avoided by constraining source parameters such as depth, mechanism, and moment/source-time function with independent data.

We also present numerous observations of anomalous timing and amplitude of regional phases and show how incorporation of two-dimensional structure can explain many of these observations. Based on these observations, and the predictive capability of our simulations, we develop a simple model that can accurately predict the timing of such phases.

Key Words: wave propagation, three-dimensional earth models, regional seismic phases

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OBJECTIVES

Model Validation and Development

We are comparing data and numerical simulations of regional wave propagation at selected stations in the Middle East and North Africa to validate and improve our regional earth model (MENA1.1, Walter et al., 2000) and begin development of model-based correction surfaces for regional identification and discrimination. For example, we compare data and simulations for events at RAYN, a broadband seismic station in Saudi Arabia (Figure 1).

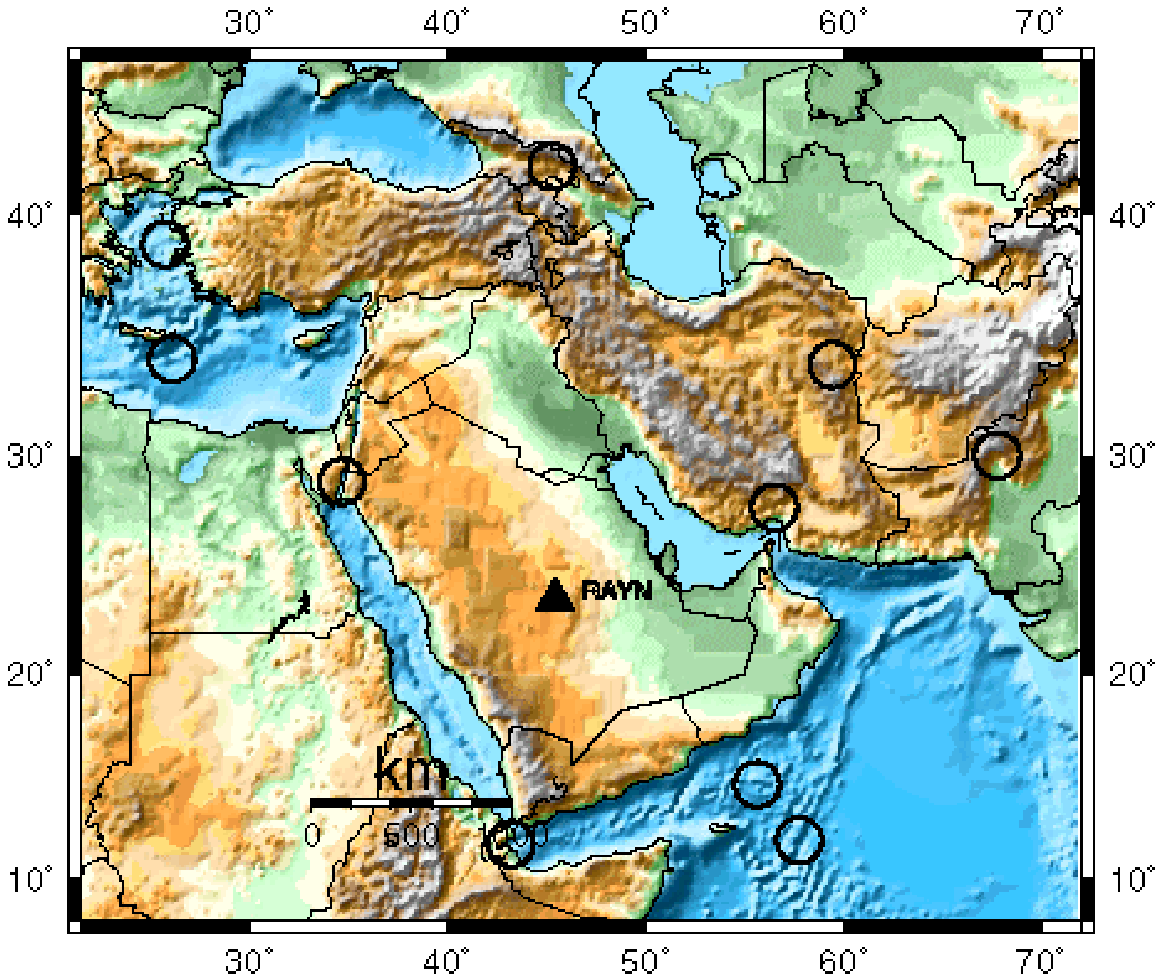

Figure 1, Map of selected events in the vicinity of RAYN. These events are being used to test and validate the MENA model.

Selected cross-sections and waveform comparisons are shown in Figure 2. In comparison to AK135 (the standard one-dimensional earth model used for most monitoring purposes), the MENA model generally produces a much better representation of the observed data. However, in some cases, results for the MENA model are similar to those of AK135 and differ significantly from the observed data. These differences indicate a need for additional calibration.

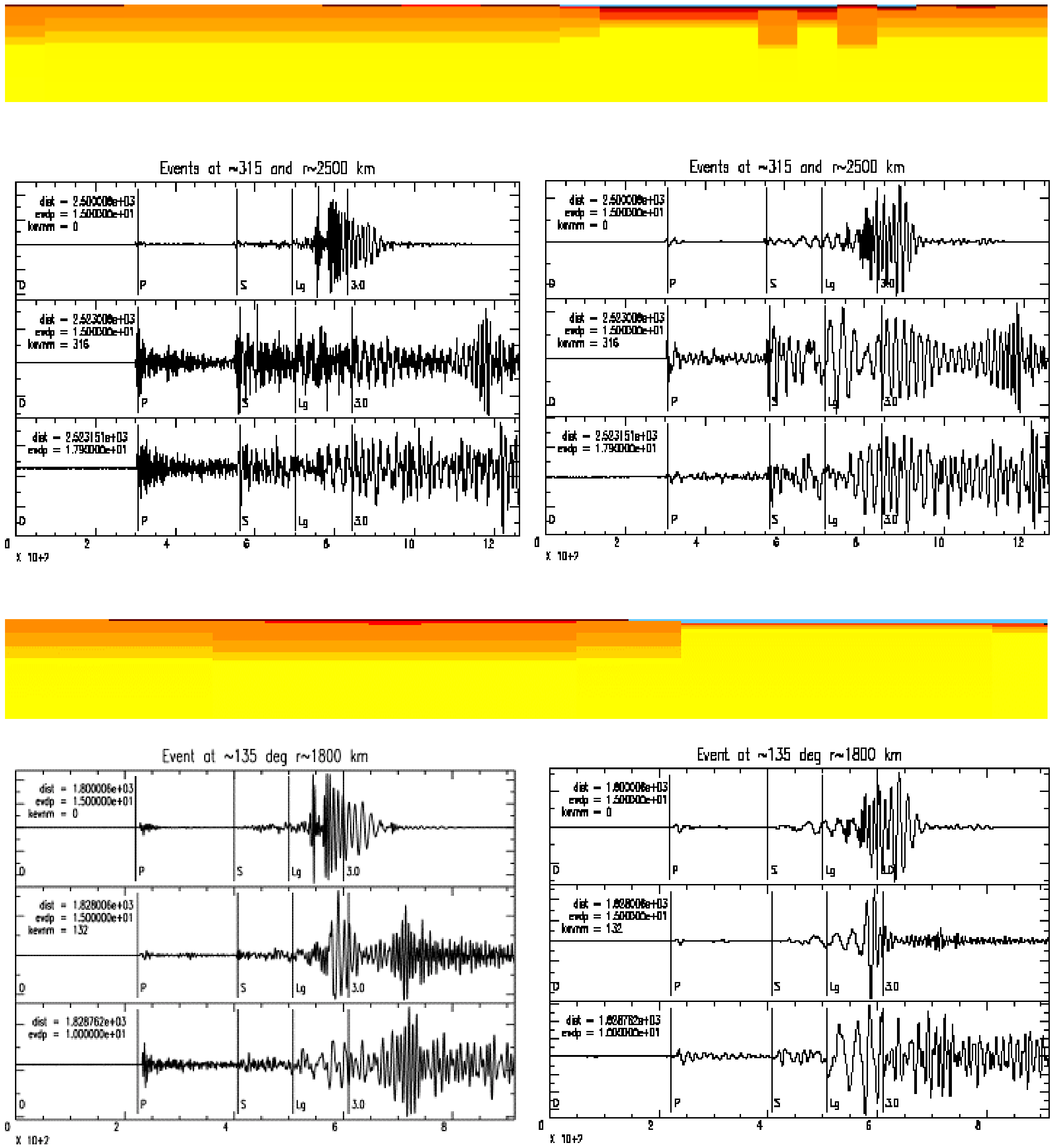

Figure 2. Comparison of data and simulations for earthquakes recorded at RAYN. The top parts of the figure show the Earth cross-section with RAYN at the left edge followed by the data and synthetics for an event at approximately 2500 km. The bottom part of the figure shows the cross-section, data, and synthetics for an event to the southeast at a distance of approximately 1800 km. In each sub panel with waveforms, the top trace is the predicted ground motions based on the AK135 earth model. The middle trace is the ground motion prediction based on the MENA model. The bottom trace is the observed data. The sub panels on the left side are broadband data and synthetics. The sub panels on the right side are narrow band filtered around 20-s period. Visual inspection clearly shows that the MENA model improves upon the conventional AK135 model. This improvement is verified quantitatively by comparing observed and predicted group velocity measurements.

In order to quantify the improvement provided by the MENA model, we compared observed and predicted group velocities (Figure 3). As shown in Figure 3, we found that the MENA model significantly reduced the difference between the observed and predicted group velocities relative to AK135. Furthermore, in cases where it did not reduce the residual it was usually as good as AK135. These discrepancies suggest that additional calibration of the MENA model is warranted.

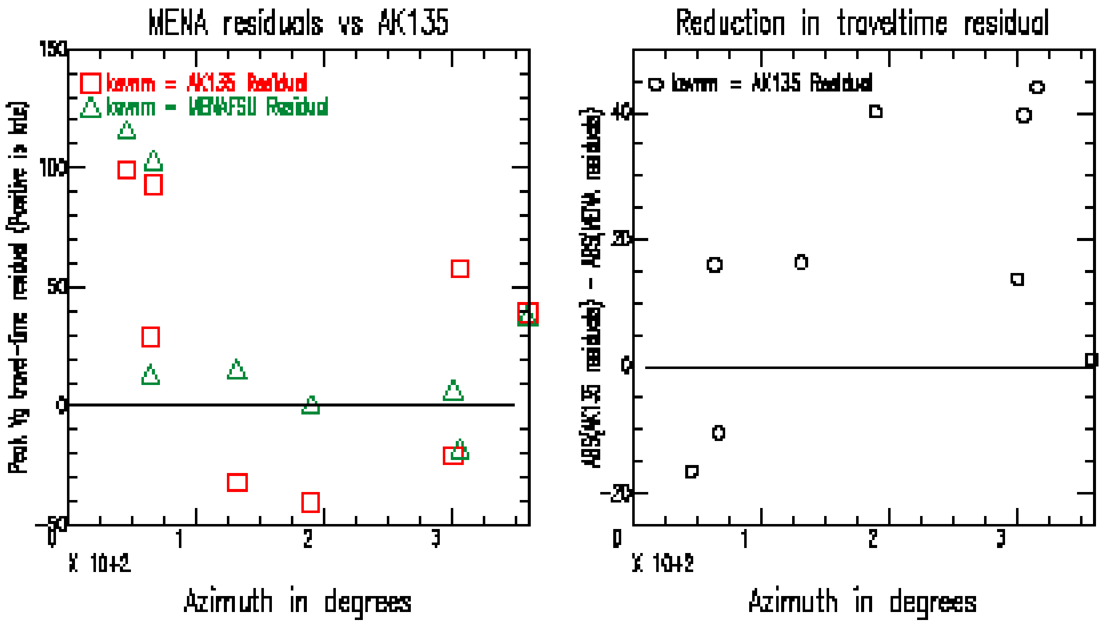

Figure 3. Comparison of observed and predicted group velocities for the MENA and AK135 models. a) Difference between observed and predicted group velocities for the MENA model (triangles) and AK135 (squares). b) Relative improvement in predicted group velocities (AK135 residual - MENA residuals).

Constraints on Source Parameters

When possible, we try to avoid potential trade-offs between variability due to source parameters and structure, by estimating source mechanism and depth based on a combination of regional, far-regional, and teleseismic data (e.g., Goldstein and Dodge, 1999, Goldstein et al., 2000). Broadband (Approximately 0 to 2 Hz) body waveforms from the far regional and teleseismic data are modeled using generalized ray synthetics. The regional data are modeled at longer periods (approximately 10 to 100 s) using reflectivity. Grid search and simplex algorithms are used to find the best depth and mechanism for both data sets. When available, we also use source parameters estimated by organizations such as the NEIC and Harvard CMT group.

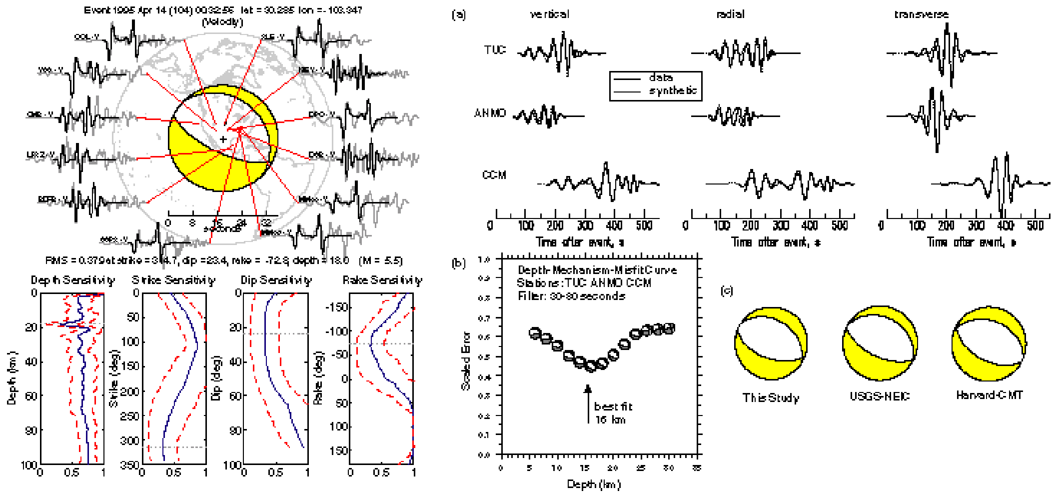

Figure 4. Constraints on source parameters from long-period regional, broadband far-regional, and teleseismic data help reduce uncertainties and trade-offs between source and model parameters. For example, modeling of far-regional and teleseismic bodywave data (left) can provide sharp constraints on depth. Modeling of regional data (right) can provide additional constraints on depth and more accurately constrain mechanism and structure.

Regional Phase Identification

We use numerical simulations of regional wave propagation phenomena to explain and identify anomalous regional S-wave phases (Sx) observed throughout the Middle East and North Africa (Figure 5). Understanding and predicting these anomalous regional phases is important because they can have a significant effect on the performance of regional monitoring techniques.

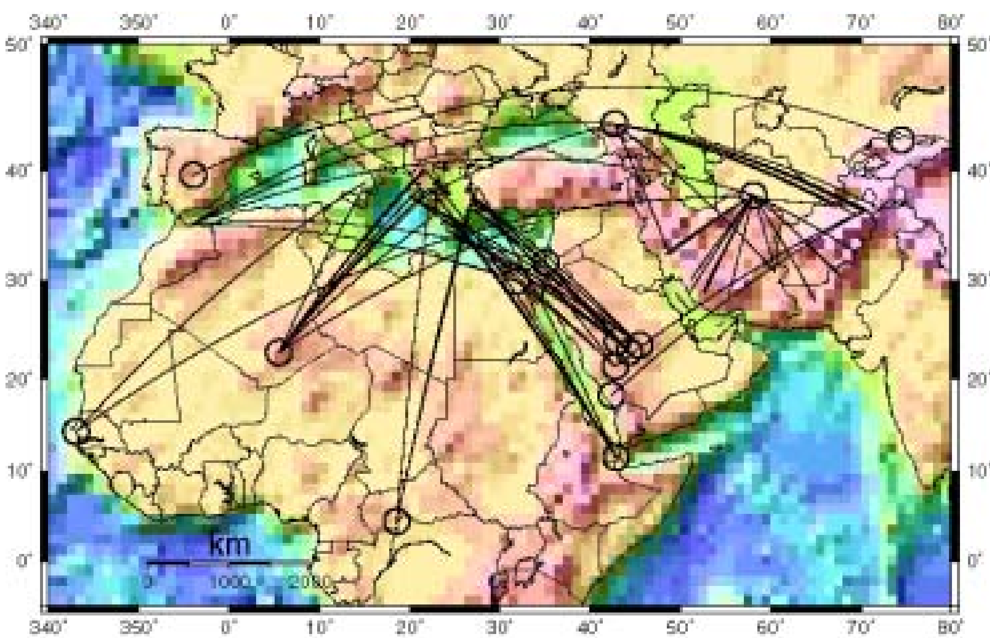

Figure 5, We have observed anomalous, late arriving S-wave phases at numerous stations throughout the Middle East and North Africa. Station locations are indicated as open circles. Event locations are at the tips of the solid lines.

These S phases are considered anomalous and labeled as Sx because they are distinct arrivals with arrival times that differ significantly from what would be predicted for standard regional S phases such as Sn or Lg. They are also consistently observed from event to event at the same station (Figure 6). For example, the Sx phases in Figure 6 have group velocities that are significantly slower than Sn and much too fast to be Lg.

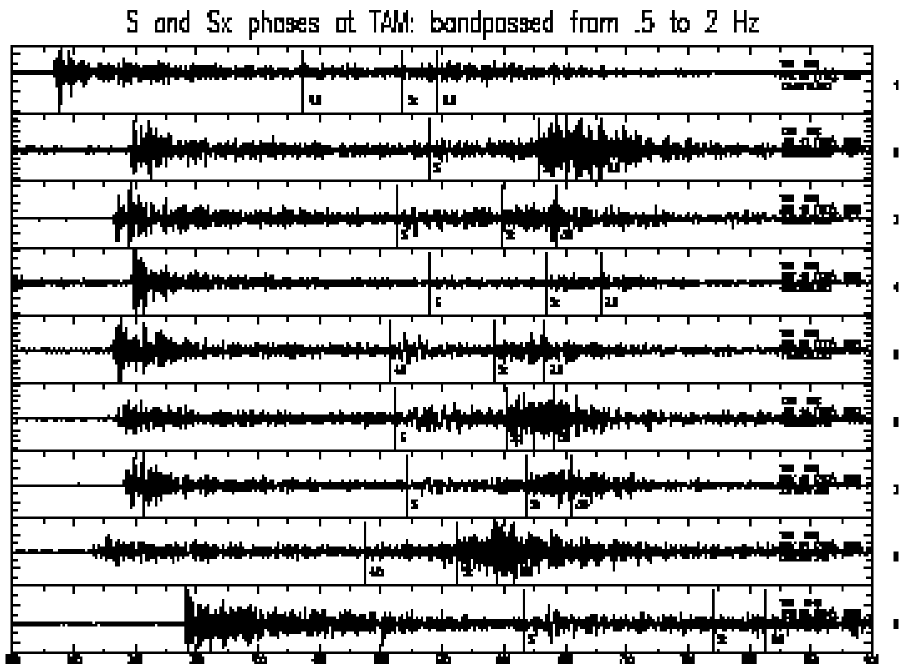

Figure 6. Sx phases recorded on vertical components at TAM. Group velocities of the Sx phases are significantly slower than Sn and much too fast to be Lg.

Based on our simulations, we claim that the Sx phases are conversions from Sn to Lg or Lg to Sn, depending on the geometry of the crust-mantle boundary between the source and receiver. We have developed a simple analytical model, based on the difference in arrival times of the mantle S-waves and anomalous Sx phases, to predict the locations of the conversion points (Figure 7). These conversion points are found to correlate well with sharp changes in the depth of the crust-mantle boundary (Figure 8).

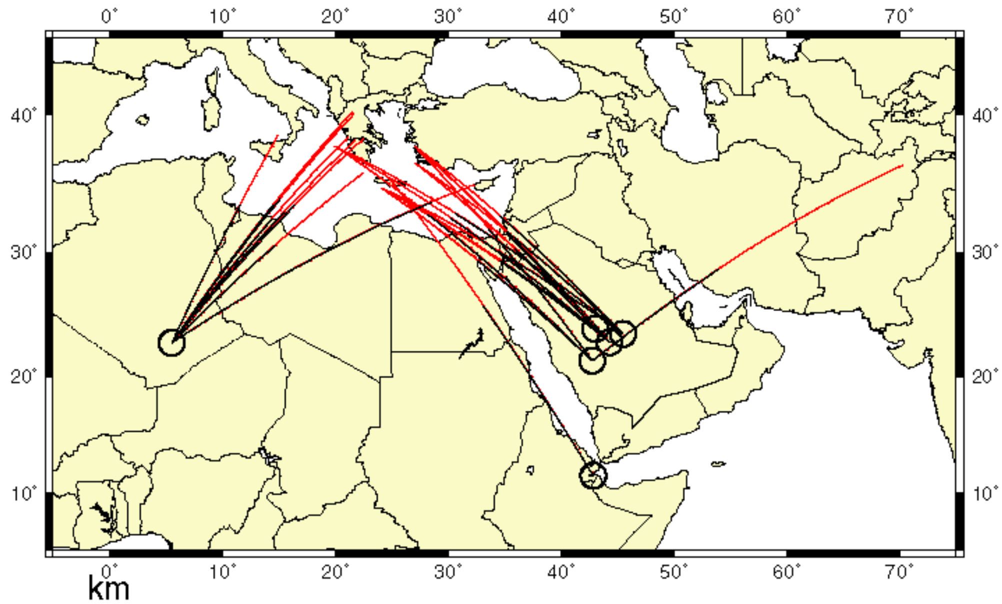

Figure 7. Predicted Sx conversion points based on differences in S and Sx travel times. The bottom ends of the black lines between the station and event pairs indicate the conversion points.

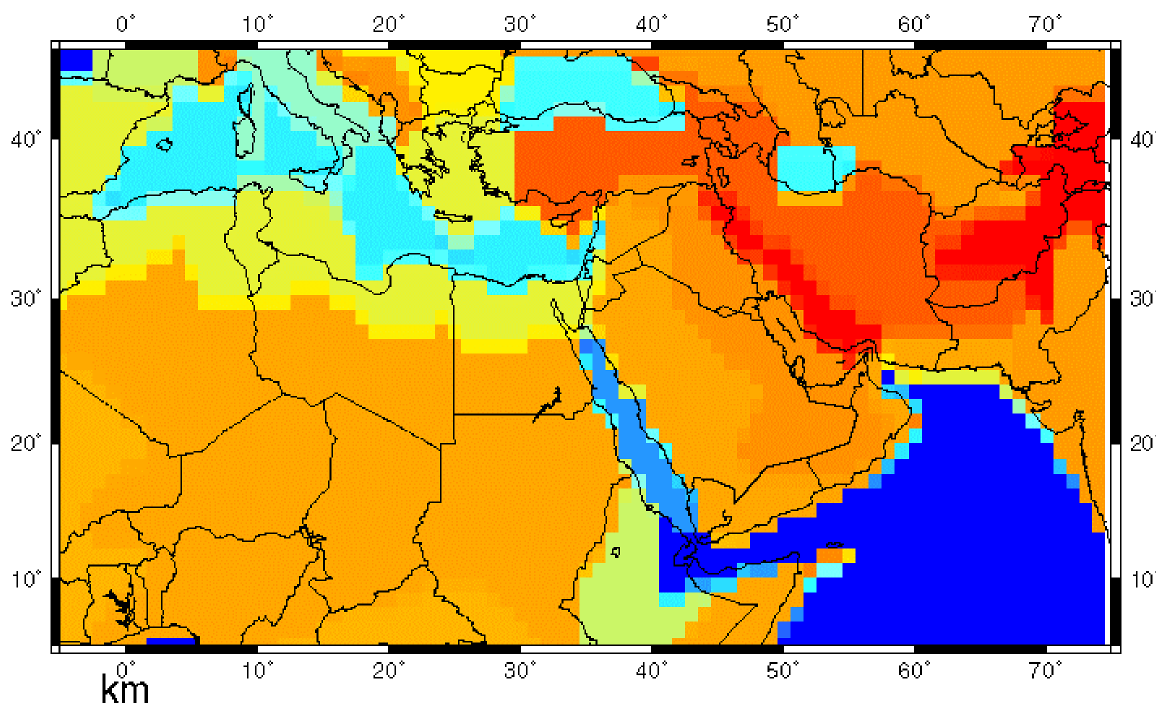

Figure 8. Color-coded map of Moho depth. Upper right (red) areas are deep, and upper left and lower right (blue) areas are shallow. The estimated Sx wave generation points, indicated by the change in line tone in Figure 7, occur at places with rapid changes in crustal thickness.

CONCLUSIONS

We are using two-dimensional finite-difference wave propagation modeling capabilities to help develop and validate a regional model for the Middle East, North Africa, and the former Soviet Union. Based on quantitative comparison of observed and predicted group velocities, we have shown that the MENA model is a significant improvement upon AK135, the conventional model used for monitoring purposes. Qualitative comparison of observed and predicted waveforms also indicates significant improvement.

In order to avoid trade-offs between source and structure, we have developed and are utilizing techniques for estimating source parameters from regional, far-regional, and teleseismic data. These techniques can provide high-resolution constraints on source depth and mechanism.

We have documented anomalous regional S phases (Sx) and shown that a simple model based on conversions at sharp changes in crustal thickness can explain the observed anomalous arrival times. The ability to predict such anomalous phases is important for the development of robust regional monitoring techniques.

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